

USAARL Report No. 77-21

PHYSIOLOGICAL PARAMETERS ASSOCIATED WITH EXTENDED HELICOPTER
FLIGHT MISSIONS: AN ASSESSMENT OF PUPILLOGRAPHIC DATA

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September 1977

Final Report

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 77- 21	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PHYSIOLOGICAL PARAMETERS ASSOCIATED WITH EXTENDED HELICOPTER FLIGHT MISSIONS: AN ASSESSMENT OF PUPILLOGRAPHIC DATA		5. TYPE OF REPORT & PERIOD COVERED Final
7. AUTHOR(s) David B. Anderson, Ph.D. Wun C. Chiou, Ph.D.		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bio-Optics Division (SGRD-UAO) US Army Aeromedical Research Laboratory Fort Rucker, AL 36362		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Aeromedical Research Laboratory SGRD-UAC Fort Rucker, AL 36362		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA 1498
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) US Army Medical R & D Command Washington, DC		12. REPORT DATE September 1977
		13. NUMBER OF PAGES 20
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) This document has been approved for public release and sale; its distribution is unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Pupillography, Flight Fatigue, Pupil Response to Light, Pupil Diameter, Blinking Frequency		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Six Army aviators served as subjects in a study of various psychological and physiological parameters associated with extended helicopter flight mis- sions. This report presents the results of the initial pupillographic data collected in this study as well as the problems encountered and the recommended solutions. It was shown that the waveform characteristics of the pupillary reflex response to light were irregular. Furthermore, the blinking frequency increased and the pupillary amplitude varied as a function of loaded flight task. Results also revealed that the average pupillary diameter was smaller in the		

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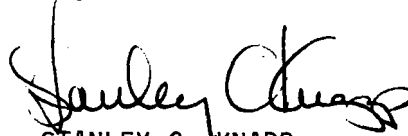
morning than in the evening. This report recommends the future use of pupillography in which an evaluation of pilot alertness is needed.

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SUMMARY

Six Army aviators were used to study various psychological and physiological parameters of flight fatigue. This study reports the characteristics of the pupillary reflex response to light and of the pupillary amplitude variation. It was found that the waveform characteristics of the pupillary reflex response to light were relatively irregular. Qualitative analyses revealed that the blinking rate increases and the pupillary amplitude varies as a function of loaded flight task. The average pupillary diameter was smaller in the morning than in the evening. This third flight day showed the smallest average pupillary diameter for all subjects. Results from this study should be evaluated with other potential flight fatigue parameters such as the blood and urine tests, EKG, etc. in order to derive more meaningful interpretations of the complex underlying flight fatigue mechanism.

A handwritten signature in black ink, appearing to read 'Stanley C. Knapp', written in a cursive style.

STANLEY C. KNAPP
Colonel, MC
Commanding

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the Naval Aero-medical Research Laboratory (NAMRL), Pensacola, Florida, for the use of their pupillometer; to Dr. James Grissett (NAMRL) for his helpful suggestions on this project; to SP Steve Evans, SP George Rice and SP L.A. Akers for their assistance in data collection; and to Dr. Michael Lees for his assistance in the statistical analysis.

INTRODUCTION

The use of electronic pupillography in the study of pupillary response to various stimuli has been pioneered by Lowenstein and Loewenfeld⁸⁻¹⁸. These workers in collaboration with Feinberg¹⁴ have described the influence of acute and chronic fatigue on spontaneous pupillary movement and pupillary response to light. They found that when a subject is fatigued: (a) the size of the pupil becomes smaller; (b) the amplitude of the pupillary response to light is diminished; (c) the waveform of the pupillary response to light is changed to a characteristic square, W-shaped, V-shaped or flattened reflex response; and (d) waves of spontaneous pupillary contraction and dilation, called hippus, accompany periods of increasing sleepiness^{3,19,20}.

Yoss and his associates have also studied pupil size and spontaneous pupillary waves in relation to various levels of wakefulness²³⁻²⁷. They have defined five levels of wakefulness from alert to very sleepy based on pupil size, amplitude and duration of pupillary waves and eyelid activities. As a person becomes fatigued his pupil diameter can decrease by as much as 55%, and the durations of pupillary dilation and contraction waves increase. It is often accompanied by severe ptosis and frequent eyelid closures.

The relationship between the waveform characteristics of the pupillary reflex response to light and various types of fatigue has been subjected to much investigation in the past few decades. Ferree and Rand have shown the close correlation between irregular shapes of the pupillary reflex response to light and various light stimulus intensity levels⁵. Lowenstein and his associates have systematically analyzed waveform characteristics of the pupillary reflex response to light with respect to chronic, physical and pathological fatigue¹¹⁻¹⁶. They claimed that analysis of the waveform characteristics of the pupillary reflex response to light provided an objective means for evaluating fatigue. Obtaining results from cats, monkeys, rabbits, and humans, they concluded that both efferent pathways in the autonomic systems (sympathetic and parasympathetic) participate in the production of the spontaneous pupillary waves. On the other hand, Meyer, et al¹⁷ and Yoss, et al²⁵ state that the parasympathetic system plays the primary role for the spontaneous pupillary waveforms.

Yoss and his associates have studied the ability of automobile drivers and commercial airline pilots to remain alert^{23,24,27}. Using electronic infrared pupillography, they measured pupil size of subjects sitting in total darkness for a period of ten minutes. Subjects were categorized into five levels of wakefulness. They found that those subjects exhibiting the lowest levels of wakefulness during the test period have also had problems remaining alert during driving or flying.

The purposes of the present study are to: (1) analyze pupil size, and spontaneous pupillary movements to light during field testing of pilots participating in extended helicopter flights; (2) assess the validity of the data; (3) and assess the value of pupillographic measurements on the evaluation of pilot alertness. This study references a subproject of fatigue indices including biochemical, physiological, psychological and performance measurements. Preliminary results of the biochemical and physiological correlates have been previously reported^{2,4,7}.

METHODS

Subjects

Six volunteer rotary wing aviators who had just graduated from their flight training program at the Army Aviation School, Fort Rucker, AL, were the subjects for this study. Their age ranged from 23 to 26 years and their previous flight time ranged from 200 to 500 hours.

Experimental Procedure

Two subjects were used per test period. A typical schedule for a test period was as follows: subjects arrived at the research facility on Friday evening to allow two normal nights rest before the experiment began. Briefings of the experimental procedure on Saturday were conducted. On Sunday, control data for all experimental parameters such as biochemistry, dynamic visual acuity, and pupillary reflex responses were collected. At 0430 hours Monday, the test procedures as outlined in Table I were initiated. The subjects were not allowed to rest until 0100 hours AM the following day. After three and one-half hours of sleep, they were awakened and instructed to start another test cycle. The pilots were instructed to continue this routine for as long as they could. The flights were terminated by the experimentors on Friday in the late afternoon even though the pilots were willing to continue. The pilots had a full night's sleep and were not awakened until 0600 hours Saturday which was the first post control day. The subjects returned to their home for the succeeding two days and then returned for the final postcontrol test day (Monday). The total duration of the experiment was six weeks.

In each session, subjects were tested for pupillary reflex, one subject at a time, twice a day (approximately 0730 and 1930 hours). They were dark adapted for five minutes and then were instructed to observe a dim red circular fixation light. Two short flashes were presented to each subject at the beginning of each session. This was followed by 10 minutes of pupillary measurements in complete darkness. At the end of the session two final flashes were presented. The interval between the two successive flashes was three seconds and the duration of

TABLE I. DAILY TEST SCHEDULE

TIME	ACTIVITY
0430	Subject awakened
0500-0600	Flight
0615-0800	Breakfast and Testing
0800-1145	Flight
1200-1400	Lunch and Testing
1400-1745	Flight
1800-2000	Supper and Testing
2000-2345	Flight
2400-0100	Snack and Testing
0100-0430	Sleep period

each flash was 0.2 seconds. The luminance for the flash stimulus was 1.8 footlambert. The pupillary reflex responses with the normal blinking responses were recorded on an analog strip chart recorder.

The pupillary data was obtained with a TV pupillometer Model 800S (Whittaker Corp., Waltham, MA) which utilizes a closed-circuit television system to measure the pupil size. A low intensity, near-infrared General Electric light source illuminated the eye without discomforting or distracting the subject. Pupil diameter, in millimeters, was presented as a direct readout on a strip chart recorder (Hewlett Packard Corporation, Cupertino, CA), with an amplitude scale range from 0 to 10 mm.

The integrated base consisted of a fixed and a movable platform. It also had a chin rest and a forehead restraint, adjustable for height. Supports for the camera and light source were attached to the movable platform, which was precisely adjustable for lateral position and distance from the eye. Source of experimental variation in measures of this type has been previously discussed by Tryon²².

RESULTS AND DISCUSSION

Pupillary Reflex Response to Light

The results of the pupillary reflex response to light have been analyzed by a waveform method and previously reported⁴. This method of waveform analysis described an Amplitude Transformation Waveform (ATW). Briefly, the ATW utilizes a differential method to extract out the principal characteristics of the pupillary reflex response to light^{11,17}. The technique is widely used to classify various irregular waveforms such as W, U or V shapes. Using ATW, it was shown that the appearance of negative ATW values during certain flight days could possibly be used as a measure of fatigue⁴.

It was found that at flight day 3 in the morning sessions, all six subjects showed a negative differential ATW. The negative amplitude implies that the pupillary amplitude over-reacts to the stimulus of light. On the following flight days they again returned to a positive ATW suggesting adaptation.

The use of waveform changes in the pupil reflex response to light as an index of fatigue has the advantage that it requires only a few minutes measurement time as opposed to the Yoss procedure²⁵ of 10-15 minutes of measurement in darkness. This is important in terms of subject morale as well as time efficiency. In order for this measurement to be useful, however, a number of problems have to be dealt with:

(a) The optimum time and intensity of the light flash needs to be established using fresh and fatigued subjects. (b) A verification and validation of waveform changes under the conditions of the proposed experiment needs to be accomplished. (c) The data acquisition needs to be automated to allow for the mathematical manipulation of the data. The conventional differential technique used by various investigators^{11,17} to classify irregular waveforms such as w, u, or v shapes is timeconsuming if data acquisition is not automated.

Pupil Size and Spontaneous Pupillary Movements

The pupil of the human eye shows fluctuations in size known as pupil unrest or hippus²¹. Some investigators have described this pupillary hippus as random noise²⁰ while others have concluded that hippus has a periodic component³.

Changes in these spontaneous pupillary movements in darkness is an objective measurement of fatigue in normal subjects who are fatigued by inadequate rest¹⁵. If an individual is placed in an environment devoid of extrinsic alerting stimuli, his pupils will remain large if he is alert. If he is not alert his pupils will decrease in size. There are normal differences in pupillary size of alert persons. Pupil size becomes smaller with age, therefore size is not as important as the ability to maintain the size during the test period.

Figures 1 and 2 are examples of spontaneous pupillary responses during ten minutes of darkness. Figure 1 is the 0730 hours morning measurement and Figure 2 is the afternoon measurement at 1930 hours. Opposite each tracing is listed the day of measurement. Post control day one was the first non-flying day after a full night's sleep. Post control two is the final recovery day taken after two days rest. The vertical axis is pupil diameter in millimeters (the amplitude between two bars is 8 mm). The horizontal axis is time from 0 to 10 minutes. When a blink occurs the amplitude is reduced to zero (indicated by an arrow). The average pupil size over all subjects for each measurement period is presented in Table II. Overall size in AM was $5.2 \pm .1$ mm while in the P.M. it was $5.9 \pm .1$ mm. Significant differences in average pupil size were noted between subjects ($p < .005$). Pupil diameter was smallest in the morning of flight days 3 and 4 but the difference between days was not significant. This correlated very well with that of the ATW data previously described⁴.

It is interesting to note that pupil diameter was significantly smaller in the morning than in the evening ($p < .01$). This would be interpreted by Yoss' criteria²⁵ to mean that the pilots were more alert at 1930 hours than they were at 0730 hours. Self rating of fatigue over

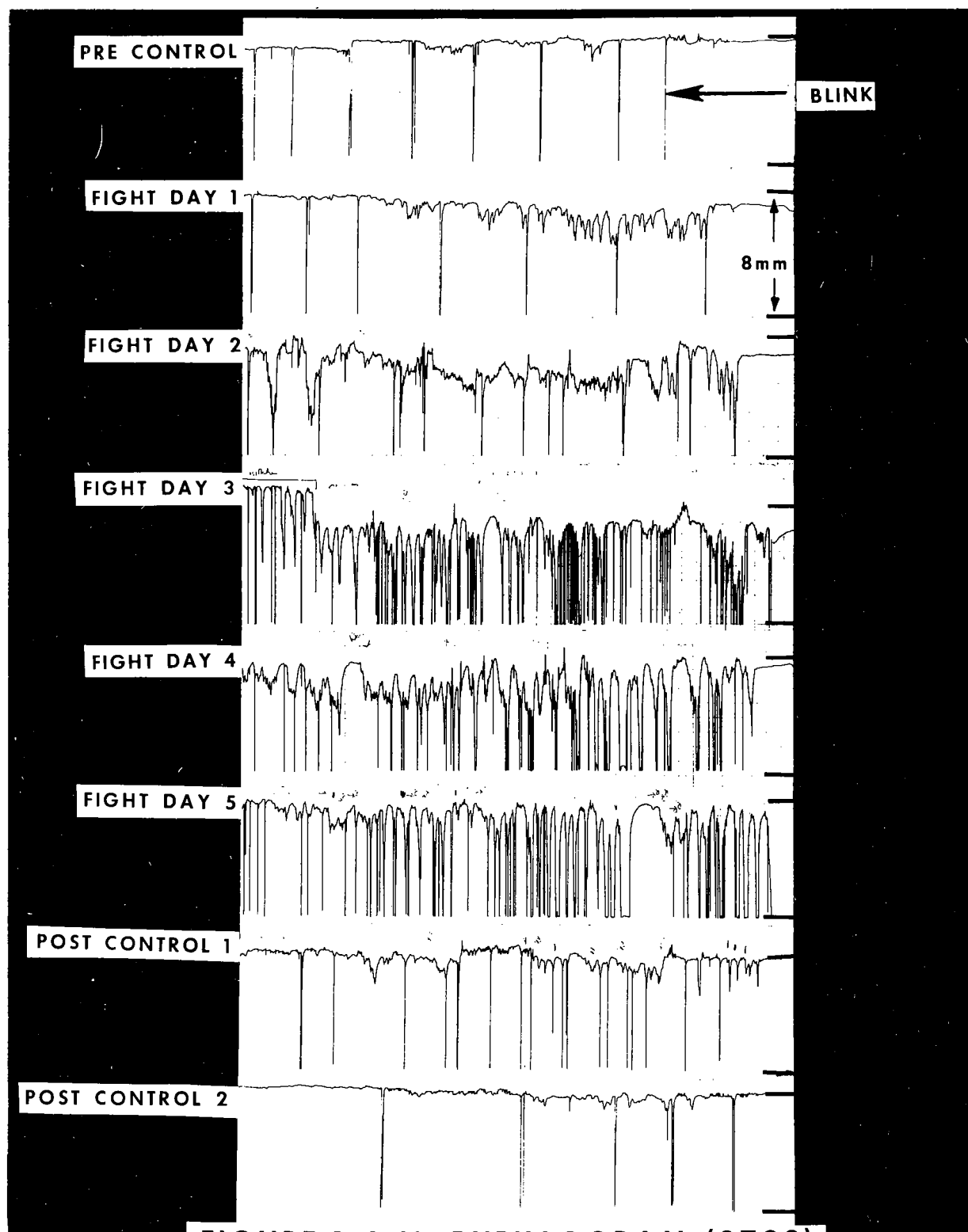


FIGURE 1 A.M. PUPILLOGRAM (0730)

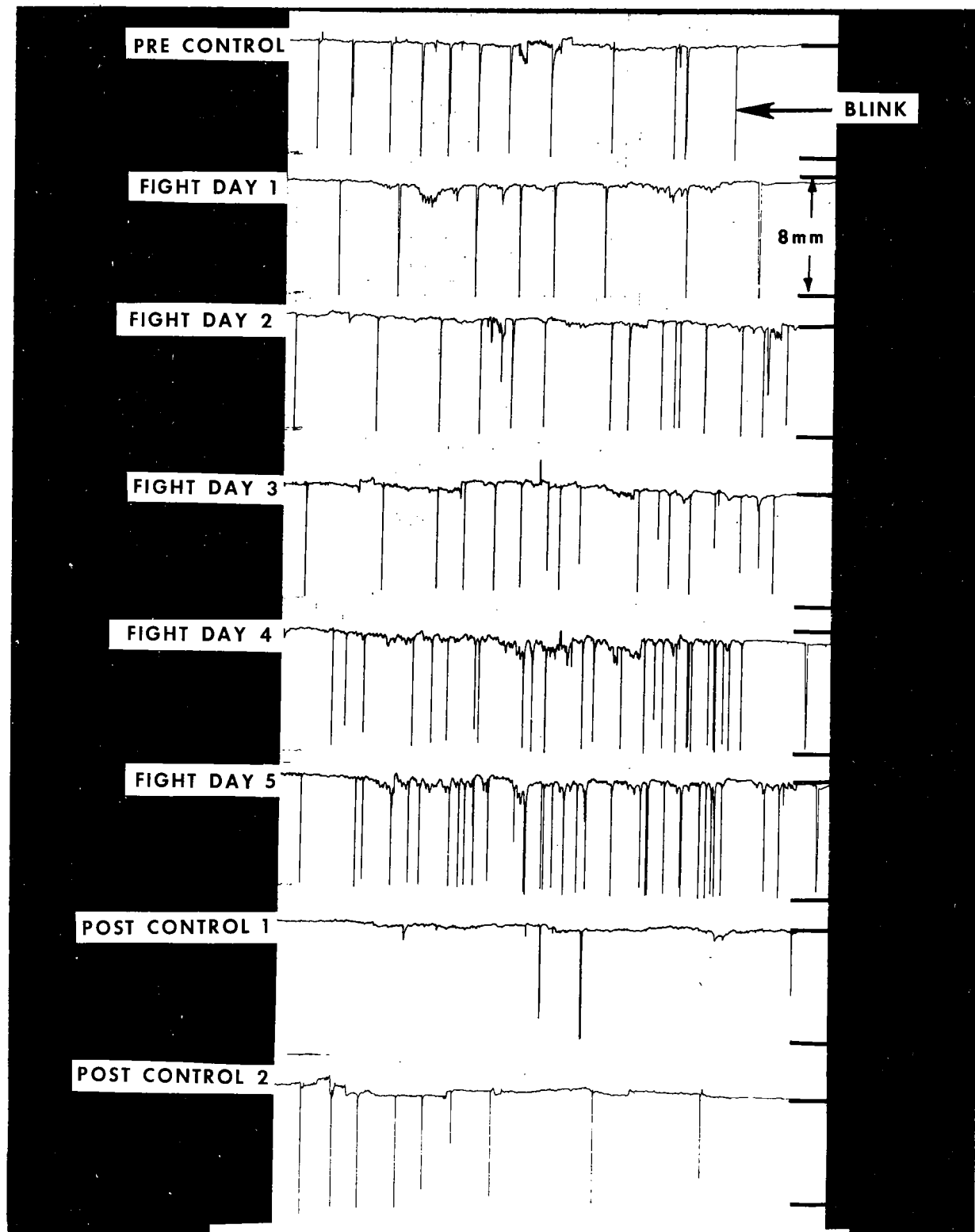


FIGURE 2 P.M. PUPILLOGRAM (1930)

TABLE II. AVERAGE PUPIL DIAMETER (mm) \pm S.E.M.

	PRE CONT	FLIGHT DAY					POST CONT 1	POST CONT 2	OVERALL
		1	2	3	4	5			
AM (0730)	5.6 \pm .7	5.6 \pm .5	5.1 \pm .5	4.0 \pm .7	4.6 \pm .9	5.5 \pm .6	5.5 \pm .6	5.7 \pm .7	5.2 \pm .1
PM (1930)	5.9 \pm .6	5.6 \pm .8	5.9 \pm .6	5.9 \pm .6	6.0 \pm .6	6.2 \pm .6	6.2 \pm .6	6.1 \pm .7	5.9 \pm .1

all subjects showed no differences between the morning (0745 hours) and evening (1945 hours) sessions (Table III). During precontrol and post-control 2 subjects felt more fatigued in the evening. However as the flight days progressed, the pilots gradually switched to feeling more fatigued during the morning session.

A qualitative examination of the data revealed greater blink frequency during the morning measurements than during the evening. In addition, the amplitude of the pupil fluctuations were greater in the morning than in the evening sessions, again suggesting a higher level of alertness during the 1930 hours session. There was a definite increase in spontaneous pupillary waves (both frequency and amplitude) during the flight days as compared to control days. Furthermore, it was observed that the activity of this hippus was increased markedly just prior to lid closure. The early work of Lowenstein and Loewenfeld^{12,13} also reported that the process of fatigue was accompanied by an increasing disintegration of autonomic reflex function which became maximal when the subject was on the verge of sleep.

One of the major problems in measuring pupil size in fatigued pilots was the development of bilateral ptosis. It was difficult to distinguish between ptosis and a true change in pupil size. Therefore, it was impossible to quantify spontaneous pupillary activity in this experiment. The obvious solution is an eyelid crutch. We had considered an eyelid crutch but opted in favor of pilot comfort. We believe now, however, that an eyelid crutch is a necessity, and, if administered as suggested by Yoss²⁵, it may not be excessively uncomfortable.

It must also be emphasized that pupil diameter can be affected by numerous factors²². Therefore a constant, stimulus-free test environment is absolutely essential.

CONCLUSIONS

Pupillographic measurements during ten minutes of darkness following the experimental format of Yoss and his coworkers offers a sensitive measure of alertness. From the experience gained in this study, troublesome problem areas were identified for correction if the technique is to be reliable in fatigue evaluation studies.

Within the constraints of problem areas identified qualitative and limited quantitative analysis of the data provide the following conclusions:

(1) Average pupil diameter during morning session (0730 hours) was less than during the evening session (1930 hours). This implies that

TABLE III. FEELING TONE¹ AT TIME CORRESPONDING TO PUPILLOGRAPHY TESTING

	PRE CONTROL	FLIGHT DAY					POST		OVERALL
		1	2	3	4	5	CONTROL 1	CONTROL 2	
AM (0745)	6.3	7.7	12.5	13.8	15.3	14.1	7.7	5.0	10.3
PM (1945)	7.8	10.5	13.3	13.3	13.8	14.2	5.8	5.7	10.5

NOTE: A score of 0 indicates no fatigue; 20 indicates extreme fatigue.

¹Subject Fatigue Self Appraisal

the subjects were in general more alert in the evening than in the morning.

(2) Fluctuations in pupil diameter were greater in morning than in the evening. Again, this indicates that the subjects were more fatigued in the morning than in the evening.

(3) Pupil diameter was smallest during the third and fourth flying days and was highest during control days. In view of the statistical significance, it is tentatively concluded that the third or the fourth flight day was the fatigue "hump" to be overcome.

(4) Blinking frequency was greater and eyelid closures were more prominent during the later flying days. Since the data were not automated, the statistical analysis of blinking frequency was incomplete. Thus, the conclusion of the blinking frequency as a fatigue parameter was qualitative.

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